LONG TERM CLIMATE RECORDS FROM POLAR ICE

BERHARD STAUFFER
University of Bern, Switzerland

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Abstract. One of the great challenges in climate research is to investigate the principal mechanisms that control global climatic changes and an effective way to learn more about it, is the reconstruction of past climate changes. The most important sources of information about such changes and the associated composition of the atmosphere are the two large ice caps of Greenland and Antarctica. Analysis of ice cores is the most powerful means we have to determine how climate has changed over the last few climatic cycles, and to relate this to changes in atmospheric composition, in particular to concentrations of the principal greenhouse gases – CO_2, CH_4 and N_2O (carbon dioxide, methane, and nitrous oxide).

Transitions from cold ice age climates to warmer interstadials have always been accompanied by an increase of the atmospheric concentration of the three principal greenhouse gases. This increase has been, at least for CO_2, vital for the ending of glacial epochs. A highly simplified course of events for the past four transitions would then be as follows: first, changing orbital parameters initiated the end of the glacial epoch; second, an increase in greenhouse gases then amplified the weak orbital signal; third, in the second half of the transition, warming was further amplified by decreasing albedo, caused by melting of the large ice sheets in the Northern Hemisphere going parallel with a change of the ocean circulation.

The isotopic records of Greenland ice cores show evidence for fast and drastic climatic changes during the last glacial epoch. Possible causes and mechanisms of such changes and their significance as global climatic events are discussed here. Ice core results also enable the reaction of the environment to past global changes to be investigated.

It will also be discussed how reliable stable isotope records are as a local temperature proxy and how representative paleoclimatic results from Greenland and Antarctica are in relation to global climate.

1. Introduction

The snow deposited in the central parts of polar ice sheets is buried by subsequent snow falls and compacted under the pressure of the overlaying snow. It is densified to ice by a sintering process and penetrates with time deeper and deeper into the ice sheet as it also moves toward the coast. Figure 1 shows schematically a cross section through the Greenland ice sheet. It is in equilibrium concerning volume and shape if the annual loss of ice, melted at the coast or breaking off as ice bergs, is compensated by the annual snow deposition in the interior of the ice sheet. It is obvious from Figure 1 that the age of the ice is increasing with depth. Therefore, core drilling into an ice sheet allows the collection of a well stratified and complete set of precipitation samples from the past few tens to several hundred thousand

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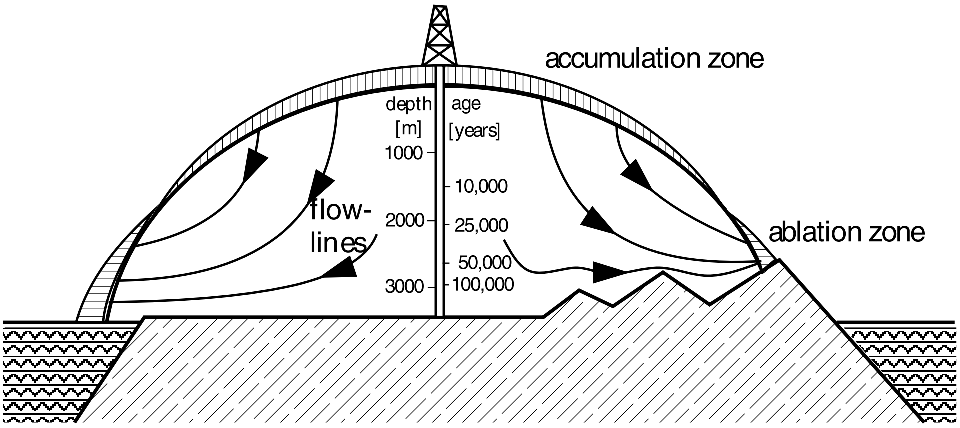

Figure 1. Schematic vertical cross section of an ice sheet resting on bedrock. Snow deposited at the surface of the accumulation zone will follow the flow lines and melt or break off as ice bergs in the ablation zone. In the central part of the ice sheet the age of the ice is getting continuously older with increasing depth. The annual layer thickness is getting smaller due to the plastic flow of ice. The given depth and ages are valid for a cross section through Summit in Greenland.

years. The analyses of these samples provide a variety of important proxies for climate and environmental conditions at the time of snow deposition or ice formation respectively.

– The stable isotope ratio in sea water is about 0.002 for $^{18}O/^{16}O$ and about 0.00015 for $D/^{1}H$. Deviations from these mean values given as δ-values (relative deviation in per mille) are a proxy for the local mean annual surface temperature. From annual snow samples collected at locations with different annual surface temperature in Greenland the following empirical relation was derived (Johnsen *et al.*, 1992):

$$\delta^{18}O = 0.67 \times \bar{T}_s[^\circ C] - 13.7‰ \tag{1}$$

However, this relation is not necessarily the same for past temperature changes. Indeed, borehole temperature data show that it was far from this relation in the past as will be discussed in section 4. For a temperature record it is not relevant whether it is based on $\delta^{18}O$ or δD values.

– Volcanic eruptions emit large amounts of dust, vapour and gases into the atmosphere. Large explosive eruptions around the world are characterised in ice cores mainly by an elevated sulphate concentration (Hammer, 1980). It is possible to look in such selected layers for volcanic fragments which allow an identification of the volcano. Until now no significant global cooling lasting longer than a few years could be observed after volcanic eruptions (Hammer *et al.*, 1980).

– The concentration of various chemical compounds depends on the activity and distribution of corresponding sources, the transport mechanisms to the polar ice sheets and the transfer from the atmosphere into the snow cover. Measurements allow the determination of pre industrial atmospheric concentrations.

Longer records show that several compounds showed systematic variations before human impacts. Ice from the last glacial epoch is enriched in most aerosols (Petit *et al.*, 1981). It is also possible to get information about the oxidation capacity of the atmosphere in the past by measuring the concentration of reactive species like hydrogen peroxide and formaldehyde (Staffelbach *et al.*, 1991). In Greenland, changes of ammonium concentration and of the concentrations of carboxylic acids give information about changes of the bioactivity of the North American continent (Fuhrer and Legrand, 1997).

– In the central parts of large polar ice sheets the surface temperature does not reach the melting point, not even during summer days. Ice is formed at such places by a dry sintering process. Atmospheric air, filling the pore space between firn grains, is more and more driven out with the densification of the firn. A final amount, about 10% by volume, is finally enclosed in bubbles. This air has the composition of the atmosphere at the time of enclosure. It has to be kept in mind that the enclosed air has a younger age than the surrounding ice (Schwander *et al.*, 1993). By the analysis of air extracted from well dated ice samples the atmospheric composition in the past can be determined (Raynaud *et al.*, 1993).
– Radioisotopes like ^{10}Be and ^{36}Cl are produced by cosmic radiation in the atmosphere and deposited to the earth and, therefore, also to the snow surface. The concentration of such isotopes in ice can be used to reconstruct a record of past cosmic radiation as discussed by J. Beer in this volume.

Information from all these proxies is only valuable if the age of the ice (time since snow was deposited) and the age of the enclosed air can be determined. An age scale can be obtained by:

– Counting annual layers: isotopic ratios and the concentration of several chemical compounds show seasonal variations, which can be identified by measurements and counted if the annual accumulation is sufficiently high. For the ice cores from central Greenland it was possible to count annual layers down to about 1750 m, corresponding to 14500 years BP (Johnsen *et al.*, 1992).
– Comparison with reference horizons like volcanic eruptions, variations in gas and dust concentrations (Hammer, 1989; Blunier *et al.*, 1998).
– Calculations based on ice flow properties and based on estimated accumulation rates. The accumulation rate is expected to depend on mean annual air temperature (Johnsen and Dansgaard, 1992).

2. The Last Four Climatic Cycles

Late Quaternary climate (about the last 1 Million years) is characterised by changes between glacial epochs and warm interstadials. Glacial epochs are characterised in Antarctica by much colder temperatures, reduced precipitation rates and enhanced storminess. Interstadials are considered to be similar to our present climate. The

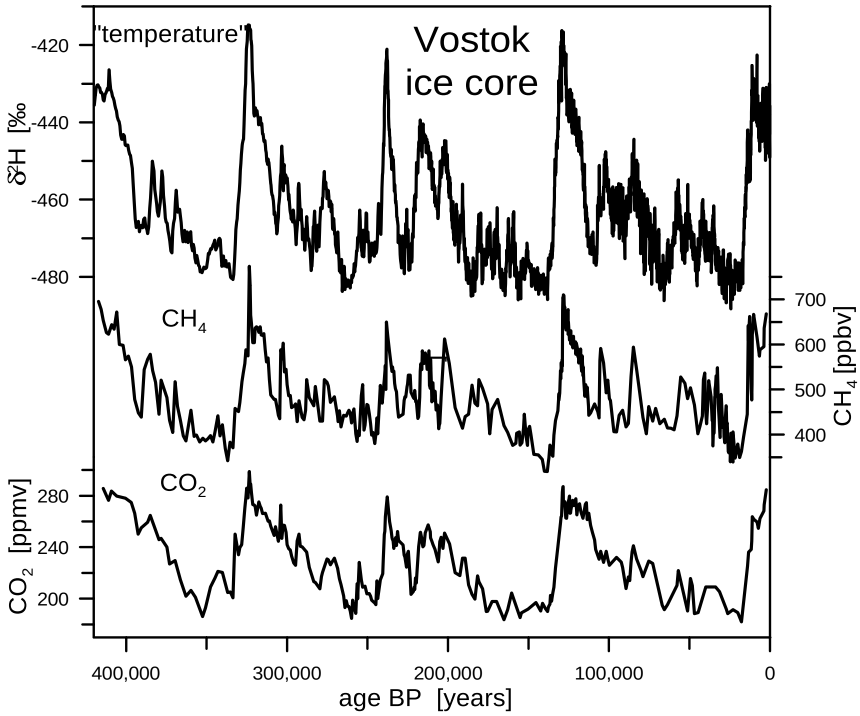

Figure 2. Deuterium, carbon dioxide and methane record of the Vostok (East Antarctica) ice core on a linear age scale according to Petit *et al.* (1999). The age resolution for the CO_2 measurements are between 1,500 and 6,000 years, for CH_4 measurements between about 100 and 4,500 years. The accuracy is better than 1‰ for Deuterium, about 3 ppmv for CO_2 and 20 ppbv for CH_4.

δD record in Figure 2 representing a temperature proxy for Vostok (Antarctica) (Petit *et al.*, 1999) shows that the main transition between glacial to warm epochs started at about 335,000 years, 245,000 years, 135,000 years and 18,000 years BP. From this one would infer a roughly 100,000 year periodicity. Time-series analysis confirm this periodicity and there is general agreement that it is caused by changing orbital parameters (in this case especially eccentricity) of the Earth. However, the nature of the interaction between the orbital parameters, which cause only a minor variation of the total solar irradiance and its latitudinal distribution, are still unclear.

Figure 2 shows as well the records of the two most important greenhouse gases CO_2 and CH_4 (Petit *et al.*, 1999). The records show that the atmospheric concentration of both gases was never as high as today during the past 420,000 years (present values: 370 ppmv for CO_2 and 1,700 ppbv for CH_4) and that there is a strong correlation between the temperature represented by the δD record and the two greenhouse gas records. The interplay of temperature and the atmospheric greenhouse gas concentration is of course of special interest.

The atmospheric methane concentration was varying between 350 and 550 ppbv during glacial epochs and increased up to 700 ppbv during interstadials. Methane

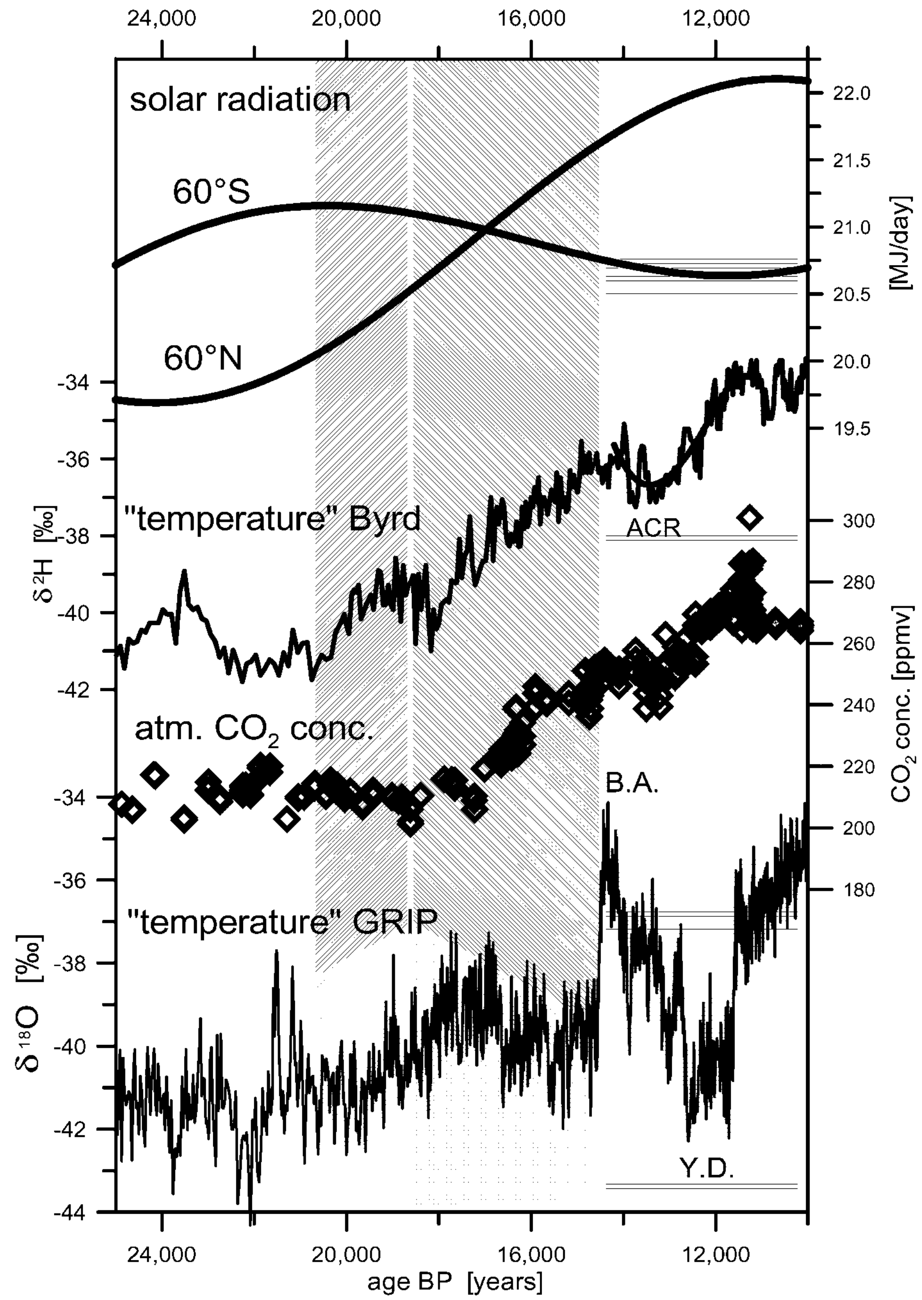

Figure 3. Solar radiation for the summer month (JJA for Northern Hemisphere, DJF for Southern Hemisphere), Antarctic temperature, atmospheric CO_2 concentration measured on Byrd ice core and Greenland temperature (Johnsen *et al.*, 1992) on a common time scale to illustrate a possible mechanism for the transition from the last glacial epoch to the Holocene (Petit *et al.*, 1999). The time intervals with different hatchings are explained in the text.(ACR: Antarctic Cold Reversal; B.A.: Bølling/Allerød; Y.D.: Younger Dryas)

was produced in pre industrial times mainly by wetlands (Chappellaz *et al.*, 1993). The main sink is the reaction with OH radicals in the atmosphere. It is assumed that the variations of the atmospheric concentrations are mainly caused by variations of the sources, which means larger and more productive wetlands during warmer climate and less sources during cold epochs. A feedback on climate by radiative forcing of atmospheric methane variations is small.

The atmospheric CO_2 concentration increases at each transition from about 180 ppmv to $280 - 300$ ppmv. According to Petit *et al.* (1999) the CO_2 increase is (within uncertainties) in phase with the temperature increase. On the other hand Fischer *et al.* (1999) report, based on measurements on the same core that the start of the temperature increase preceded the start of the CO_2 increase by $500 - 1,000$ years. The question of lags and leads is a very important one, but the identification of a time lag of $500 - 1,000$ years is very difficult taking into account the uncertainties of the age difference between ice and enclosed air bubbles. Even if a time lag would be confirmed CO_2 could still be an important amplifier for the temperature increase which lasts itself several thousand years.

Petit *et al.* suggest based on their results the following simplified scenario for glacial-interglacial transitions which is shown schematically in Figure 3:

- The temperature in Antarctica starts to increase due to a high solar irradiance during the austral summer months at high Southern latitudes.
- In a second phase the warming is amplified by an increasing CO_2 concentration.
- In a third phase warming due to an albedo feed back becomes dominant caused by the melting of the large ice sheets in the Northern Hemisphere.

Causes for the observed CO_2 increases are not clear yet. From the Vostok results covering the last two transitions, Broecker and Henderson (1998) concluded that the Southern Ocean is likely to be the main player regulating atmospheric CO_2. Similarities between CO_2 concentration and Antarctic temperature for the previous two transitions, as well as other parts of the records, add further support to the idea that the Southern Ocean does indeed have a key role (Petit *et al.*, 1999). However, all hypotheses about the linking mechanisms (changes in CO_2 solubility, phytoplankton productivity, iron fertilization etc.) all have weaknesses at present. The sequence of events excludes the possibility that the CO_2 concentration increased just as a cause of the mean ocean surface temperature or a rise in sea level.

3. Fast Climatic Variations During the Past Glacial Epoch

Figure 4 shows part of the δ^{18}O record from the GRIP ice core drilled at Summit in the centre of the Greenland ice sheet. Only the last 50,000 years are presented to allow more details to be shown (Dansgaard *et al.*, 1993).

Clearly visible is the transition from the last glaciation to the Holocene. The difference of the δ^{18}O value of 8‰ would correspond to a local temperature in-

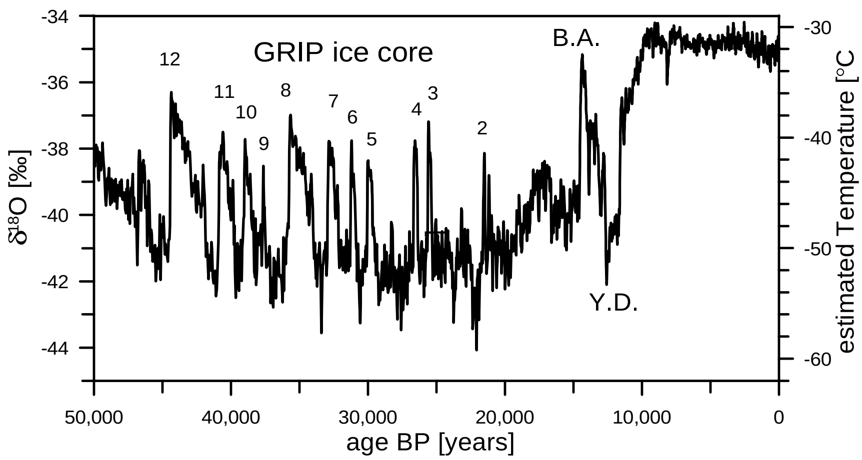

Figure 4. Part of the continuous δ^{18}O record from the GRIP ice core along a linear time scale, covering the last 50,000 years. Glacial interstadials, so called Dansgaard/Oeschger events are numbered $12-2$. B.A. is event 1, known in Europe as the Bølling-Allerød interstadial. The cold period Younger Dryas is marked by Y.D.. (Dansgaard *et al.*, 1993)

crease of 12°C according to the relation found for the spatial dependence between δ^{18}O and mean annual surface temperature given in the introduction. However, a different relation has to be applied for the transition as will be discussed in the next chapter. So the local temperature increase is about 24°C according to our present knowledge (Johnsen *et al.*, 1995; Cuffey *et al.*, 1995). While temperature increases slowly and continuously in Antarctica at the end of the last glaciation, according to the Vostok record, the increase in Greenland shows large fluctuations. Temperature also started to increase slowly around 20,000 years BP, but a first clear, abrupt and fast temperature increase is observed at $14,450 \pm 200$ years BP. It is especially astonishing that the local temperature increased in two decades by more than 10°C. The following warm period, known in Europe as the Bølling/Allerød, gave way after less than two millennia to a cold period, known as Younger Dryas in Europe. The Younger Dryas period was terminated again by an abrupt temperature increase at 11,550±70 years BP the final transition from the last glacial epoch to the Holocene in Greenland (Johnsen *et al.*, 1992; Severinghaus *et al.*, 1998). The two fast temperature increases and the Younger Dryas period as a whole are an important key for understanding the mechanisms responsible for large global climatic changes.

Fast and drastic temperature variations are also seen in the GRIP record during the last glacial epoch. This fast variations, called Dansgaard/Oeschger events, have been a confirmation of the same variations observed already in the Dye-3 (South Greenland) ice core (Dansgaard *et al.*, 1984). All Dansgaard/Oeschger events start with an abrupt temperature increase of several degrees in a few decades, followed by a slow temperature decrease to low glacial temperatures again.

CO_2 analyses along the Dye-3 and the GRIP ice core show large concentration variations of the order of 50 ppmv parallel to Dansgaard/Oeschger events (Stauffer *et al.*, 1984; Anklin *et al.*, 1997). However, measurements on Antarctic ice cores did not confirm these variations (Neftel *et al.*, 1988), which have to be global due to the short mixing time of CO_2 in the atmosphere of about two years. New measurements show indeed that the Greenland records do not give the true atmospheric record because CO_2 can be produced by chemical reactions in the ice despite the low temperatures of $-20°C$ (Dye-3) and $-32°C$ (GRIP) respectively (Tschumi and Stauffer, in press). Antarctic CO_2 records are more reliable due to the lower impurity concentrations in the ice. Recently it became possible to synchronise the age scale of Greenland and Antarctic ice core records to about 200 years uncertainty as will be discussed in section 6. Therefore, it is now possible to compare Antarctic CO_2 records with Greenland δ^{18} records. This comparison shows definitively that the large concentration variations with an amplitude of 50 ppmv are an artefact. On the other hand they suggest that there have been variations going parallel with the Dansgaard/Oeschger events which have a long duration but with an amplitude of only $10 - 20$ ppmv (Stauffer *et al.*, 1998).

Most of the Dansgaard/Oeschger events recorded in Greenland ice cores have parallels in the record of ice-rated debris found in deep sea sediments from the North Atlantic (Bond *et al.*, 1993; Bond and Lotti, 1995). This correlation provides some clues concerning possible mechanisms which cause the fast variations observed in Greenland but not in Antarctica (or at least only strongly attenuated there). Based on observations and model calculations there is general agreement today that the Dansgaard/Oeschger events are correlated with variations of the deep water formation in the North/Atlantic which controls to a great deal the deep ocean circulation, the so called conveyor belt (Broecker, 1994). The deep water formation is caused at present by very cold and saline and, therefore, dense surface water. An input of fresh water caused, for example, by large ice masses calving into the North Atlantic from the large glacial ice sheets covering North America and North Europe, could decrease or stop the deep water formation. This would have lead to a cooling in the North Atlantic region. Resumption of deep water formation after a certain time would cause the abrupt temperature increases observed in Greenland ice cores (Paillard, 1994). If this mechanism can be confirmed, there still remains the question about the cause of large ice berg discharges at irregular intervals. The break off could be caused by pure ice dynamic properties (a growing ice sheet gets unstable when its margin reaches the continental borders), or there could also be an influence of extraterrestrial quantities like Earth orbital parameters or variations of the solar luminosity. It is obvious that these fast variations are also an important key for the understanding of mechanisms governing global climate.

4. How Reliable are Stable Isotope Records as Proxy for the Local Temperature?

The δ^{18}O and δD values of precipitation, based on simple physical laws, depend on the condensation temperature (Dansgaard, 1964). However, the good correlation between the mean δ^{18}O value of an annual precipitation sample and the mean annual temperature is an empirical finding based on spatial temperature distributions and corresponding variations of the stable isotope ratios (Dansgaard *et al.*, 1973). The question remains, as in the case of other proxies like tree ring width, pollen and foraminifera distributions, whether this spatial dependence ("modern analogue method") is the same for the climatic variations observed in the past. For ice cores it was recently possible to test this hypothesis by two new tools, inverse modelling based on bore hole temperature measurements and based on the thermal diffusion of gases in the permeable firn layer.

The firn temperature at 10 m depth corresponds, in regions where surface melting can be neglected, to the mean annual surface temperature (Paterson, 1994). Changes in the mean annual air temperature propagate into the ice by diffusive heat flow and by ice flow. The temperature profile through an ice sheet thus provides a record of past surface temperature, modified by heat diffusion, ice flow and a small amount of heat generated by ice deformation, and in deeper strata by the geothermal heat flux (Dahl-Jensen *et al.*, 1998). The reconstruction of the surface temperature based on the temperature profile is difficult. The record of high frequency events is lost entirely by heat diffusion especially in deeper layers. The reconstruction is not unambiguous, several temperature records can lead to the same temperature profile. However, temperature records e.g. based on stable isotope profiles can be tested by comparing with the temperature profile. Such tests have been made independently for the GISP-2 and the GRIP bore hole in Central Greenland. Both tests showed that the temperature shift between the glacial epoch and the Holocene had to be larger as predicted by the δ^{18}O record assuming a relationship of 0.67‰/°C (Johnsen *et al.*, 1995; Cuffey *et al.*, 1995). The best fit is obtained if for this temperature variation a relation of 0.33‰/°C is applied. This leads to a temperature increase of 24°C from the last glacial maximum to the Holocene as shown on the right scale in Figure 4. However, this relation is not necessarily valid for other temperature variations like the Dansgaard/Oeschger events.

For fast temperature variations there is another tool to test temperature differences, the thermal diffusion. In a large part of the permeable firn layer, air is only transported by molecular diffusion. This causes a slight enrichment of heavier molecules at the bottom of the firn layer due to gravitation (Schwander *et al.*, 1988). If there is a temperature difference between the bottom and the top of the firn layer with diffusive mixing, there is in addition a separation of components with different masses by thermal diffusion (Severinghaus *et al.*, 1998). This process slightly alters the isotopic as well as the elemental composition of the air, which gets enclosed in bubbles. The measurement of records of the $^{15}N/^{14}N$ ratio in N_2 along an ice core section representing a fast temperature increase, allows the temperature difference to be determined. Severinghaus *et al.* determined the temperature increase at the end of the Younger Dryas period to have been 15°C. Lang *et al.* (1999) determined the temperature difference at the onset of Dansgaard/Oeschger event nr. 19 (about 70,000 years BP) to be 16°C. The comparison of these temperature increases with the corresponding increases of stable isotope δ-values allows the relations between temperature changes and e.g. $\delta^{18}O$ values to be re-assessed. For the two measured events 0.3‰/°C have been obtained for the Younger Dryas - Holocene transition and 0.42‰/°C for the onset of Dansgaard/Oeschger event 19. It is not evident that all Dansgaard/Oeschger events show the same relation. The reason for the differences in these relations seems to be changes in the seasonal precipitation distribution. In the cold parts of the last glacial epoch less winter snow was deposited.

5. How Representative are Polar Ice Core Results?

In the previous chapters some interesting and partly spectacular results from polar ice cores have been discussed. However, how representative are these results? - The Dansgaard/Oeschger events are only observed in Greenland but not in Antarctic ice cores. Therefore, they cannot be global events in the sense of synchronous temperature changes in all parts of the earth. On the other hand they would not be very interesting if they would just characterise a local phenomenon. For several events like the Younger Dryas period similar paleo records have been found in Europe and other parts of the world. However, similar records can be a pitfall as shall be shown later.

A very convincing argument that Dansgaard/Oeschger events are of global significance comes from methane records measured on ice cores. The GRIP methane record shows variations during the last glacial epoch which go parallel with Dansgaard/Oeschger events (Chappellaz *et al.*, 1993). Methane variations are caused, as mentioned already, mainly by variations of the methane sources which have been wetlands in pre industrial times. Wetlands have not existed in the neighbourhood of Greenland during the last glaciation. If the extension and activity of methane sources far away from Greenland changed synchronous with Dansgaard/Oeschger events, it is evident that it is a phenomenon which is not restricted to Greenland and not to the North Atlantic region either. The same methane variations are also observed in Antarctic ice core records despite the fact, that Dansgaard/Oeschger events are not (or only faintly) observed in the stable isotope records. Almost synchronous variations are expected due to the short mixing time of methane in the atmosphere. However, small differences of the atmospheric methane concentration between high Northern and high Southern latitudes are caused by an asymmetric distribution of the methane sources. The sources are larger in the Northern

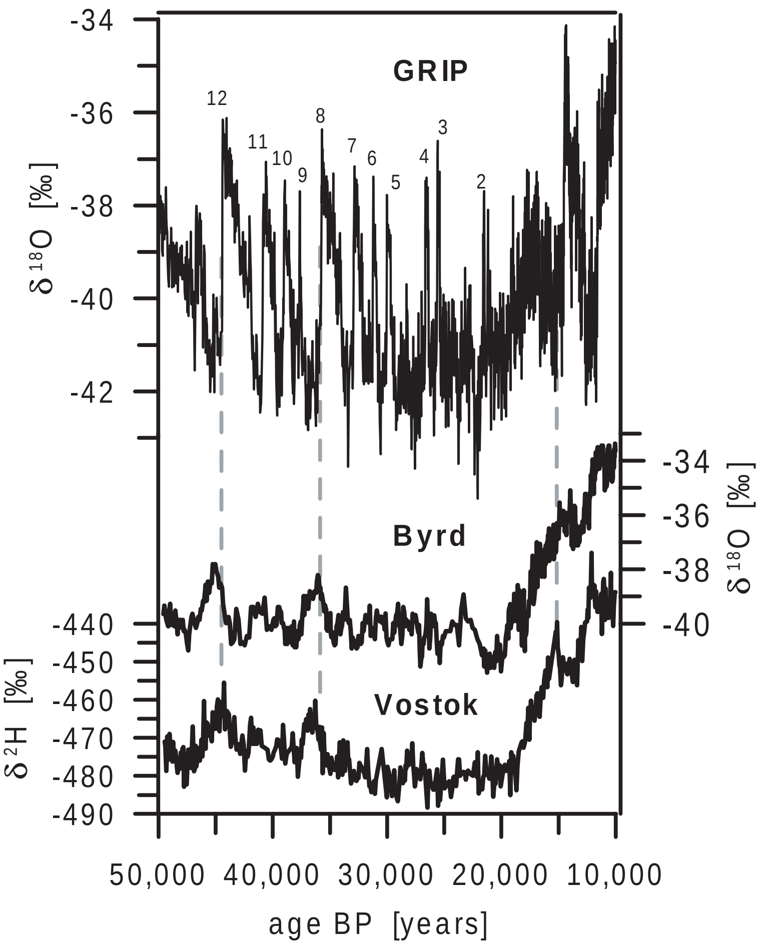

Figure 5. Comparison of the GRIP (Greenland) stable isotope record with the Byrd and the Vostok (both Antarctica) record. The scales have been selected so that the amplitudes represent about the same temperature fluctuation according to our present knowledge. The large and long lasting Dansgaard/Oeschger events 12 and 8 have a concomitant in the Antarctic records. The temperature increase occurs earlier in Antarctica than in the Northern Hemisphere. (According to Blunier *et al.* (1998) with changes).

hemisphere causing at present a concentration difference of about 140 ppbv. The concentration differences can be reconstructed for past climatic epochs. Ice core records from Greenland and Antarctica show concentration differences between North and South of −3 ppbv to +50 ppbv for the last 50,000 years (Chappellaz *et al.,* 1997; Dällenbach *et al.,* submitted). This record allows a rough estimate about the latitudinal distribution of methane sources in the past. This is a first step to reconstruct not only climate changes based on ice core records but also reaction of the biosphere to such changes. Absolute time scales of polar ice cores are not accurate enough to investigate time lags between the two hemispheres by a millennium or less. The parallel methane variations allow the age scales of Greenland and Antarctic ice core records to be synchronised. Best suited for this purpose are fast methane concentration increases at the beginning of Dansgaard/Oeschger events and at the transition from the last glacial epoch to the Holocene. The synchronisation of Greenland and Antarctic ice cores showed that the Antarctic cold reversal is not synchronous with the Younger Dryas, as previously assumed, but preceded the Younger Dryas by about a millennium (Blunier *et al.*, 1997). The largest Dansgaard/Oeschger events with a long duration have concomitants in Antarctic ice cores. However, these events in Antarctica also precede the corresponding events in Greenland by about a millennium (Figure 5) (Blunier *et al.*, 1998). This asynchrony between Antarctic and Greenland temperature supports the idea that the thermohaline ocean circulation and its changes plays an important role in the climate coupling between the two hemispheres for this kind of variations.

6. Some Remarks About Shorter Time Scales

Polar ice cores are most powerful to investigate large climatic variations with amplitudes of several degrees. They are unique because they allow temperature records with possible forcing parameters like volcanic activity and greenhouse gas concentrations to be compared. In the Holocene there is only one event, the cooling around 8,250 years BP, which is of such a kind. A clear minimum of the atmospheric methane concentration parallel to this cooling is observed. Recently it became possible to reconstruct high resolution records of the CH_4 and CO_2 concentrations which show surprising variations during the Holocene (Chappellaz *et al.*, 1993; Indermühle *et al.*, 1999). The δ^{18}O record is less spectacular. It is especially astonishing that the GRIP δ^{18}O record (Figure 4) does not show any clear signal of the climatic optimum (about 6,000 years BP). Was there no climatic optimum in central Greenland or is the δ^{18}O record misleading? Dahl-Jensen *et al.* (1998) have reconstructed the surface temperature at Summit based on the GRIP bore hole temperature profile. The reconstructed record has relatively large uncertainties but it clearly shows a broad climatic optimum in the Holocene. The temperature was 2.5°C warmer than today. The reason that the stable isotope records do not show this large temperature deviation is most probably again a change in the seasonal distribution of precipitation. It is assumed that there was a higher contribution of winter snow, and that the low δ-values of the winter snow compensated the increased mean annual surface temperature effect.

There is ample evidence that the stable isotope records are reliable proxies for the temperature variations caused by the changes between glacial epochs and interstadials and by variations like the Dansgaard/Oeschger events or the 8,200 year BP cooling (Leuenberger *et al.*, 1999). Such evidence is missing at present for more detailed variations. This does not imply that more detailed fluctuations do not provide important climatic information but there is no guarantee for it. If remarkable fluctuations are found in two ice cores or in an ice core and another paleoclimate record, this can still be accidentally. A third and fourth record will have to show if the signal is consistent. Even if a signal in stable isotope records turns out to be consistent, there still remains the question whether it is a temperature signal or something else.

Fischer *et al.* (1996) investigated various ice core records from Greenland and Canada covering the last 3,000 years. They used normalised records and applied empirical orthogonal functions to separate local noise from a common signal. For the last few centuries they compared the signal also with measurements from surrounding meteorological stations. About 50% of the variance of single records is local noise, but about 50% seems to represent a "temperature" signal for the last two centuries. Going further back in time Fisher *et al.* observe that the records from Canada and North Greenland show a "little ice age" but in records from Central and South Greenland a clear signal is missing. Fischer *et al.* (1998) stacked three ice cores from a traverse in North Greenland and obtained with the stacked record, covering the last 500 years, a clear signal of a “little ice age” with temperature minima in the late 17th century and a stronger one in the early 19th century. However, if this cooling is a large scale phenomenon, there is no reason that Central and South Greenland should be excluded. Johnsen *et al.* (1997) investigated a stacked record from Summit in Central Greenland. There is a small minimum at around 1700 AD and 1900 AD but a much stronger one in the late 14th century. Dahl-Jensen *et al.* (1998), as mentioned already, have reconstructed a temperature record based on the GRIP bore hole temperature profile at Summit. It is for methodical reasons a very smoothed record. It shows a broad significant minimum at 1600 AD and one at about 1850 AD. Fischer *et al.* have an explanation for the different behaviour of δ-records in Central and North Greenland. They suspect that the δd-records in South and Central Greenland are masked because relatively warm cyclones bring most of the winter precipitation to the Southern half of the Greenland ice sheet. In this case we would expect that the stacked record from North Greenland correlates well with the temperature record by Dahl-Jensen *et al.*. The general trend is indeed similar, however, the first minimum is about one century later in the North Greenland record and the second minimum about 25 years earlier.

The goal of this discussion was not to give a final answer about the temperature history during the past thousand years in Greenland but to demonstrate that there is certainly information about short time climatic variations in polar ice cores. However, an extraction of such information is laborious and difficult. It should be a warning about overinterpretation of records from one single ice core.

7. Conclusions

Polar ice cores are unique as a source of information about large scale climatic variations and about variations of the atmospheric concentration of greenhouse gases.

This allows the influence of greenhouse gas concentrations on past global climatic changes to be investigated. In addition polar ice cores provide information about past volcanism and about variations of cosmic radiation. There is hope that the measurement of additional chemical parameters will also allow information about changes of the global environment in relation to climatic changes to be obtained. The most powerful proxy for short term temperature changes are the stable isotope records. However, the quantitative relation between δ-values and mean annual surface temperature has to be used with caution. The stable isotope records show a relatively large local noise which makes it difficult to obtain information about temperature variations in the order of 1°C or less.

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